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A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid

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ABSTRACT

The concept of integration of distributed energy resources for formation of microgrid will be most significant in near future. The latest research and development in the field of microgrid as a promising power system through a comprehensive literature review is presented in this paper. It shows a broad overview on the worldwide research trend on microgrid which is most significant topic at present. This literature survey reveals that integration of distributed energy resources, operation, control, power quality issues and stability of microgrid system should be explored to implement microgrid successfully in real power scenario.

Contents

1. Introduction

Integration or interconnection of distributed energy resources is evolving as an emerging power scenario for electric power generation, transmission and distribution infrastructure globally based on the significant issues, such as scarcity of fossil fuel in future, widespread deployment of advanced Distributed Energy

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Resources (DERs) technologies, deregulation of electric utility industries and public awareness on environmental impact of traditional electric power generation. These issues are changing the power generation concept worldwide and opening up new challenges in the generation and distribution markets. Small non-conventional generation combined with Distributed Generation (DG) is rapidly becoming attractive because it produces electrical power with less environmental impacts, easy to install, and highly efficient with increased reliability. As the awareness on environmental issues like global warming is increasing; renewable energy sources are becoming most significant sources of energy in modern power scenario. Geographical, environmental, political and financial factors of different countries lead to increased use of renewable energy resources like wind–electric conversion system, photovoltaic system, biomass resources etc. Also the low power generation capacity of DER has motivated the need for integration of different types of DERs and loads in the form of microgrid to enhance the power generation capacity, reliability and marketability of dispersed type of microsources with a promising approach to reduce the load congestion on the conventional power system or utility grid and facilitating localized generation at customer ends. The effective integration of DERs depends on the versatile nature of DGs such as photovoltaic system, wind power, small hydro turbines, tidal, Combined Heat Power (CHP) based microturbines, biogas, geothermal, fuel cells including battery storage facilities etc. that have the potential to support conventional power system with many issues involved with their interconnections. In this perspective, IEEE P1547- 2003 is a benchmark model for interconnecting DERs with Conventional Electric Power System [1] which provides guidelines to general interconnection requirements, e.g. response to abnormal conditions including operation, power quality, and safety conditions including operation in utility grid connected and islanded mode.

1.1. Motivation

The motivating factors for this review work on integration of distributed energy resources are supported by the issues related with operation and control of microgrid including deployment of power electronic based inverters in the system, protection coordination issues and in addition, stability analysis of microgrid in steady and dynamic states of operation. These are briefly discussed in the following sections (1.1.1 to 1.1.5) as motivating factors to perform this literature survey on integration of DERs.

1.1.1. Integration of distributed energy resources: microgrid

The distributed generation (DG) is gaining immense importance in the present power scenario globally due to reduced green house gas emission, better power system efficiency, reliability and as promising approach to relief existing power system from today's stress on transmission and distribution system [2]. The distributed energy resources (DERs) are changing the manner of transmission of energy through the utility power grid, enabling consumers to have some scale of flexible energy utilizations and the power system has to be converted into small distributed energy integrated system. The integration of distributed generators based on renewable energy resources (RERs) and microsources like photovoltaic system, Wind turbine, microturbine using CHP system, fuel cells, and batteries with storage facilities etc. has initiated more recent concept of microgrid which is considered as a cluster of interconnected distributed generators, loads, and intermediate storage units that cooperate with each other to be collectively treated by the utility grid as a controllable load or generator towards an evolutionary power solution for scarcity of fossil fuel in near future [3]. The microgrid enriched with modern power electronic based technology [2,4,5] can offer higher dependability of service, better quality of power supply, and better efficiency of energy use by utilizing the available waste heat. The capacity to make use of renewable energy with modest pollution and potentially lesser cost is attractive and gains gradually more interests in many countries. Additionally, distributed generation can benefit the electric utility by decreasing overcrowding on the grid, reducing the need for new generation and transmission capacity, and offering supplementary services such as voltage support and demand response. With advancements in power electronics and control technologies, the large-scale, effective integration of a range of distributed generation and energy storage technologies into the existing electric power infrastructure may finally become possible and economically feasible.

The modern concept of microgrid is highly promising as a solution to the problem due to scarcity of fossil fuel in future in conventional power generation. It is also effective against environmental impacts of existing generating system. Operation of microgrid depends on successful integration of DERs which is related with several factors like power quality issues. The power quality issues should be carefully dealt with to achieve satisfactory values of voltage and frequency in grid connected and islanded mode of microgrid in steady state and as well as, during dynamic state i.e. transition from grid connected mode to islanded mode and vice versa. The effect of harmonics on power quality might be quantified by measuring total harmonic distortion at various important points of microgrid such as across the terminals of critical loads, DER and PCC (Point of Common Coupling).

1.1.2. Operation and control of microgrid

The microgrid, an integrated form of DERs, is normally interfaced with load and utility grid by power electronic inverters [6,2]. It can operate in grid-connected mode or in islanded mode. In grid-connected mode, the microgrid either draws or supplies power from or to the main grid, depending on the generation and load with suitable market policies. The microgrid can separate itself from the main grid whenever a power quality event in the main grid occurs [7]. Autonomous control of microsources [2] suggests that the microgrid should follow a peer-to-peer and plug-and-play model avoiding the installation of a single point of failure like microgrid control center (MGCC) and dedicated storage units, so the microsources should have integrated storage unit (Battery bank in the dc bus of the inverter).

The microgrid should disconnect itself from main grid on occurrence of abnormal condition and to be shifted to islanded mode [1,2]. The variation in voltage and frequency becomes more prominent when microgrid is switched over to islanded mode. Under grid connected situation of microgrid, the voltage and frequency are determined by the grid. When the microgrid islands, one or more primary or intermediate energy sources should be controlled by adjusting its voltage and frequency. If the frequency reaches to a very low value, the load may be temporarily shaded. Also a balanced condition is to be maintained between supply and demand applicable to microgrid. If the microgrid is exchanging power with the grid before disconnection, then secondary control actions should be applied to balance generation and consumption in island mode to ensure initial balance after a sudden fluctuation in load or generation. The microgrid is supposed to preserve an adequate power quality while in island operation with sufficient supply of reactive energy to shrink voltage sags. The energy storage device should be capable of reacting rapidly to frequency and voltage change and

exchanging large amounts of real or reactive power. The microgrid has no spinning reserves like usual grid. Most microsources have delayed response when implementing secondary voltage and frequency control. The intermediate storage units and microsources with built-in battery banks are therefore expected to offer the advantages like spinning reserves. The power electronics devices react promptly to fast demand signals and adjust the power flow levels. The implementation of communication infrastructure linking the microgrid components is another aspect considered when selecting the control approach on an islanded microgrid.

Including the above factors, the microgrid should be prepared for planned islanding which is an important aspect in microgrid concept used to maintain the continuity of supply during planned outages, like substation maintenance period etc. [7].

The new approach of microgrid automation is modeling an intelligent and self configurable microgrid system using automated demand side management or automated load management. In this type of control, microgrid central controller can communicate with the loads and directs them to isolate from the grid in real time to reduce overall demand load on the system in peak-load hours [8]. Power quality control in hybrid microgrid system is important since application of different kinds of power source would impact the quality of power supply within the microgrid and causes many control problems. In this type of hybrid system, computer based monitoring system may be provided for power quality control to resist frequency fluctuation due to random load fluctuation [9].

1.1.3. Inverter based microgrid

Microsource Controller techniques rely on the inverter interfaces found in fuel cells, microturbines, and storage technologies and one of the main features of the control design is that communication among microsources is unnecessary for basic microgrid operation. Each Microsource Controller must be able to respond effectively to system changes without requiring data from other sources or locations. The control functions include the ability to regulate power flow on feeders; regulate the voltage at the interface of each microsource; ensure that each microsource rapidly contributes its share of the load when the system islands. In addition to these control functions the ability of the system to island smoothly and automatically reconnect to the bulk power system is another important operational function [10]. Also integrating various kinds of power sources would impact the quality of power supply [9] and cause many control problems to be dealt with. The diversity in DER generation and uncertainty in use of renewable energy resources can be solved by interconnecting suitably designed parallel inverters for smooth transfer from grid connected mode to islanded mode and vice versa showing fast response. Compared to rotational machine based DGs with large inertia, the response time for inverter based DGs are less but they are more susceptible to large switching transient for which proper control and protection methods are to be implemented. Therefore, to extract advantage of fast inverter operation and avoiding large transient during mode transfer is very important for paralleling inverter based DGs in a microgrid system [11].

1.1.4. Microgrid protection and coordination issues

Short circuit fault is frequent in power system and the same is harmful for the power system components, consumer's equipments as well as personnel too. As per traditional philosophy of existing power system protection, microgrids are to be protected from large amount of short circuit currents, excessively high or low voltage due to abnormal conditions occurring on the utility grid side fault or fault in the microgrid itself. To provide proper protection and to avoid damages of microgrid and customer's equipments; protective relays are to be installed to detect the abnormal conditions and to initiate circuit breakers to isolate the fault. Since proper action is required within a few fundamental cycles, decisions are generally made autonomously based upon local information like magnitudes of abnormal voltage, current etc. [1]. In utility grid, the synchronous generators are inherently capable of withstanding large fault current which is sensed by the relays and interrupted by the circuit breakers. So cost of the power system protective devices like circuit breakers, transformers, current limiting reactors are increased due to direct interaction with that severe fault current. Another important point in this context discussed in [1], is the fast limitation of fault current which is a unique capacity of power electronics based interfacing of DGs that can further provide a great benefit due to reduction in rating, as well as cost of the expensive current carrying equipments and current interrupting circuit breakers. Also the fast response characteristic of the solid state power electronic interfaced relays can provide good protection coordination among all related protective devices in the microgrid system.

On protection technique and magnitude of fault current, the views discussed in [12] are observed which proposes that a microgrid can operate in both grid connected and islanded modes where it is interfaced to the main power system by a fast semiconductor switch called static switch, (SS). Microgrid must be protected in both the grid-connected and the islanded modes of operation against all types of faults. The major issue arises in island operation with inverter-based sources. Inverter fault currents are limited by the rating of the semiconductor devices around 2 p.u. rated current. Fault currents in islanded inverter based microgrids may not have sufficient values to use traditional over-current protection techniques. The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open for all faults. With the static switch open, faults within the microgrid need to be cleared rapidly with techniques that do not rely on high fault currents.

In [13], a small portion of distribution network model is presented as a microgrid which is a set of mixed renewable DG sources and one dispatchable source. Then from the simulation of four major fault types in each bus in both grid connected and islanded it is proposed that the standard protection methods are insufficient and the uses of digital relays connected to breakers are recommended as a solution for protection coordination of power electronics based microgrid. The protection issues for power electronics interfaced microgrid reported in [14] shows that the microgrid when interfaced to the utility grid, face the common utility power quality disturbances and flow of large line currents due to utility voltage sag can be controlled by the proposed current limiting algorithms namely, the RL feed-forward and flux-charge model feedback and both methods work by inserting large virtual RL or L impedance in series with the distribution feeder to limit the line current flow thus improving the damping performance by optimally tuning the RL or L values.

In a comprehensive survey on islanding protection of active distribution network with Renewable Distributed Generators (RDGs) [15], the DG paradigm is shown as a widespread interest in power system planning and research in recent years. The main challenge in interconnecting RDGs is the protection coordination of the distribution system with bi-directional flow of fault current unlike conventional power system including proper deployment of modern concepts as discussed in this section.

1.1.5. Stability analysis of microgrid

The stability of a microgrid, which is interconnection of several distributed energy resources, is its ability to return to normal or

stable operation after having been subjected to some form of disturbance. Conversely, instability means a condition denoting loss of synchronism or falling out of normal operation. Stability considerations have been recognized as an essential feature of microgrid planning. For proper working of microgrid, the stability problems are to be taken care of considering the steady state, dynamic and transient condition. The study of steady state stability mainly concerned with computing maximum limit of DER loading while maintaining synchronism, however, if the loading is increased gradually [16]. In a microgrid, dynamic instability more often occurs than the steady state one due to sudden fluctuation of load leading to the system oscillation which is required to be died out completely within a short period. Oscillations persisting for a long period may be a serious threat to the interconnection of DERs. Therefore, study of dynamic stability of a microgrid is essential [17].

This paper presents a brief literature survey to provide information on detailed status of advancements of DERs integration technology in the viewpoints of operation, control, protection and stability of microgrid system. The recent developments of integration techniques of DERs are discussed in Section 2. Operation and control techniques of microgrid are studied in Section 3. Power quality related issues of microgrid are discussed in Section 4. Microgrid protection and stability features are discussed in Sections 5 and 6, respectively. This literature survey is concluded in Section 7.

2. Integration of distributed energy resources

The basic assumptions of the distributed system scenario are that DERs can be used to help utilities solve performance problems of the distribution system. The fundamental requirement of this is that the distributed resources operate in parallel with the utility at all times and supply sensitive loads, which can be shut down on requirement, for example when power system disturbances occur due to line faults causing momentary voltage sag [18]. The DER technology was in transition from laboratory set up to market place in and around the year 2000. The fundamental characteristic of DER is that they are active devices installed at the distribution system level instead of at the transmission level. The DERs include generation resources such as photovoltaic system, wind energy system, fuel cells, CHP based microturbine including storage technologies such as batteries, flywheels, ultra capacitors and super conducting magnetic energy storages. The integration of DERs also implies that it also consists of dynamic active and reactive power control including load side control [19]. The future power system and electricity industry are at a technical threshold which shows a new era based on interconnection of DERs. An integrated approach towards DER adoption in the neighborhood of the distribution network was reported in [20]. The direction of this work is towards an approach that is integrated, iterative and comprehensive. At the time of that report, possibly no integration was achieved and the proposed customer adoption model has been to minimize the cost of supplying electricity to a specific customer by installing distributed generation and self generating part or all of the customer's electricity requirement. It was a step towards developing an adoption model for neighborhoods or large customer sites around a feeder, which might operate as a microgrid. As proposed in [21], due to restrictions on expansion of traditional centralized generation and distribution system in industrialized countries it would be difficult to meet future electricity demands growth at acceptable cost. Meanwhile, technological advancement of DER technology with deployment of power electronic based devices would tilt the power generation economy towards smaller scales. In addition, several numbers of dispersed type energy resources at the low voltage side may be interconnected together in a quiet distinct pattern from today's conventional power generation and the shape of this integration depends on the individual interconnection of each DER parallel to the utility grid in a semi autonomous clusters of small dispersed type sources, grouped with loads and could be termed as microgrid. The emerging generation technologies along with microsource issues and proposed microgrid concept as a way to bring values to both the utility and the customer have been explored in [22]. The rating of the distributed generation has been identified in [22] as below 500 kW. The promising technologies in DG area identified therein are photovoltaic generator, wind generator, microturbines, fuel cells etc. Due to the dispersed natures of DGs and natural uncertainties, ideas of storage system including use of power electronic based inverters have been introduced. It was realized that single type of microsources can act as a supporting solution to grid interconnection but due to the small and natural uncertainties (for solar and wind generators), a cluster of different types of microsources along with storage system, loads interfaced with power electronic inverters in integrated form was conceptualized as microgrid as shown in Fig. 1.

In the evolution of microgrid concept, it was necessary to verify the feasibility of microgrid in industrial application. The benefits of introducing distributed resources within an industrial site which is designed as a plant equipped with extensive induction machines has been reported in [23]. Based on this plant, steady and dynamic state studies have been performed. Steady state analysis is used to obtain voltage profiles, power flow

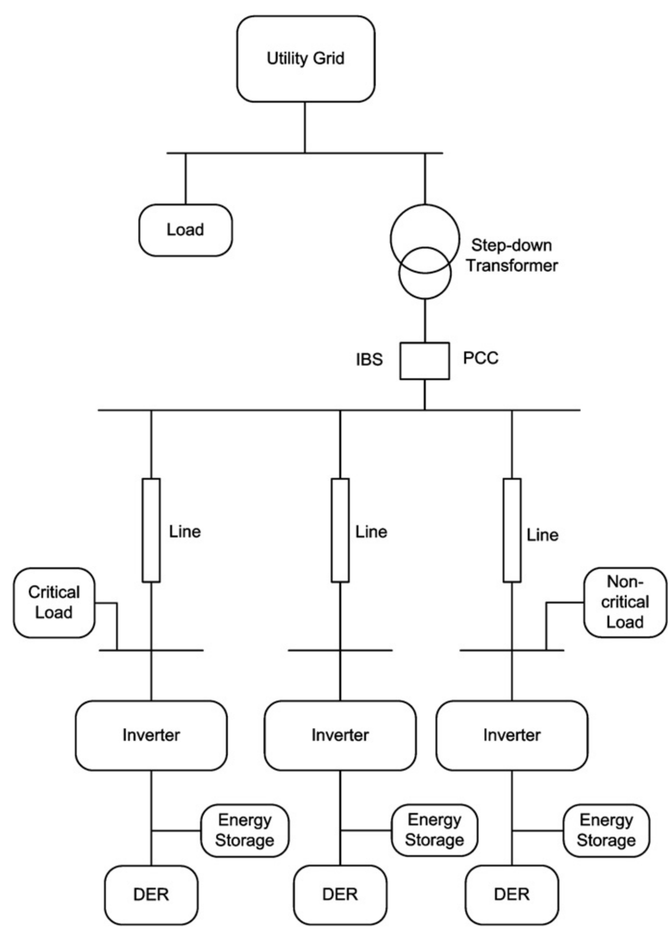

Fig. 1. Schematic diagram of an inverter based microgrid.

and system losses for different scenarios. The effectiveness of the local voltage controller during load change and load sharing features in islanded operation has been verified. The research field of DERs on behalf of CERTS to resolve the issues related with customer adoption of microgrid has been reported in [24]. In contrast to traditional power system planning, a customer oriented approach focussing DER adoption decision making at customer level has been discussed. The approach of this work for customer adoption of DER is based on established methods of minimizing the cost of meeting a known electrical load because customer scale problem for DER applications, in broader sense, has no difference with that of traditional grid. Major regulatory and technological changes of electric supply system and its remarkable implications on the operating modes have been observed in [25]. As per [8], microgrids may have a typical commercial customer such as office building, restaurant, shopping malls and grocery stores etc. To verify customer adoption of DERs, an economic model of DER adoption has been developed in Barkeley Lab to determine the optimal quantity and type of small on-site generation using DERs. This generation may be combined with loads in local semi autonomous microgrids. This type of model known as Distributed Energy Resources Customer Adoption model (DERs-CAM) can predict the DER adoption by the commercial customers. Early DER-CAM results show that typical commercial customers can adopt on-site generation under all scenarios tested. As an outcome, it was proved that typical annual electricity cost savings for the customers is about 20–25%. It has also been found that on-site generation tends to support base loads and the customers can buy power at their peaks rather than installing their own generation. Endeavors were started around 2002 to address the challenges in simulation and design of microgrid by proper analysis software by which many problems were studied prior to actual system experimentation which was single or three phases as per customer's choice [4].

A mini gas turbine generating system serving a microgrid appears to be described for first time in [26]. It has been observed that a 250 kW–500 kW gas turbine and high speed axial flux generator are effective to supply electrical power and to support heating and cooling operations for large and small industrial customers. Even it has been proved to be efficient in supplying commercial and residential customers with high load factor. A business case for DER at the San Diego biotechnology supply company BD Biosciences Pharmingen, which considers DERs for a building with 200–300 kW base load has been examined in [27]. The site is modeled as a DER-CAM, similar to a model developed at Berkeley Lab to determine economically optimal DER system for installation at a given site. The DER-CAM effort is focussed on the adoption of small scale generation (less than 500 kW) and it is suitable for the location where combined heat power and dispersed type multiple generating options are available. As per the study reported in [4], there are some factors which influence DER installation, such as, DER motivation, barriers and solutions. The motivating factors are reduction in costs, increase in distributed generations, and minimization of outage problems. Some barriers are desired contract structure, low load factor and relatively small potential size of DER project. The solutions are based on the factors like downsizing the onsite generating capacity, work around the site with low load factor demand profile proposing 300 kW natural gas engine system (two 150 kW engine) along with heat recovery system to support heating loads.

As per [28], microgrid is an aggregation of electrical loads and generators which may be microturbines, fuel cells, reciprocating engines or any of alternate power sources. In this work, an Energy Management System (EMS) is proposed to make decisions regarding the best use of generators for generation of electrical power and supplying heat. These decisions are based on the heat requirement of the local equipments, the weather, the price of electric power, the cost of fuel and many other considerations. The EMS should provide only the required information to the operator or any other authorized person for any control parameter deciding operating condition.

A review of test facilities for integrated DERs is described in [29]. The concept of integrating DERs started in the year 1999 and since its beginning CERTS has been actively assessing and reviewing DER test facilities for possible demonstrations of advanced DER system integration concept. An initial survey was conducted between 1999 and 2000 to identify the facilities and resources where distributed generation and storage system can be tested. The technological areas involved in this survey were microturbines, fuel cells, photovoltaic system, battery storage, wind and inverter/power converter system. The report described in [30] is a Berkeley Lab effort to model the economics and operation of small scale (<500 kW) onsite electricity generator based on real world installations at several example customer sites. This study is possibly the first of its kind in applying DER-CAM to a real world setting and evaluating its modeling results.

As per [31], the critical component of a microgrid is its power electronics. The majority of the microsources must be power electronic based to provide the required flexibility to ensure controlled operation as a single aggregated system. It has been proposed therein that the microgrid system must be operated despite changes in the output of individual generators and loads. It should have "plug-and play" functionality. Capacity of connecting extra load should be free of readjusting a central controller up to a preset feasible point. The main issues discussed are power flow balancing, voltage control and mode transfer (grid connected to island and vice-versa). Up to the beginning of the year 2004, in most of the cases, the microgrid had been discussed as a concept. The reporting in [31] discusses how few of the power electronic based control concepts might be realised. The remarkable issues are: the application of power flow (P&Q) control, response to the onset of autonomous operation towards islanding and resynchronization and the need of energy storage to overcome the natural uncertainties of DERs, such as, PV and Wind energy. In addition, the issues of stability of microgrid, characteristics of low voltage grid, short circuit capabilities of control and THD capabilities of control has also been reported.

In [32], the August 2003 blackout in North America is presented as a fact which had proved the possibility of failure of technologically developed modern grid. Since dependency on the grid is intensified, smaller level generation using a combination of several technologies, commonly called as distributed energy resource (DER) has emerged as increasingly competitive with large remotely central generation. Two important issues has been addressed there—(1) The inability of existing power system to provide for growing electricity needs with adequate reliability and (2) Potential benefits from combined heat and power (CHP) used in microgrids supplying loads by means of local power generation based on advanced DER technologies initiating the concept of locally controlled grid. In this perspective, CERTS microgrid has been developed and demonstrated through laboratory test as an integration of three microturbine system between late 2004 and early 2005.

As reported in [33], plug-and-play functionality can be implemented in microgrid control using inverters which can provide required flexibility. New microsources can be added to the system without modification of existing microsources. The microgrid should change its operating mode (grid connected or island) smoothly without any interruption. The control of reactive and active power should match with the dynamic needs of the loads. The microsource controller techniques depend on the inverter interfaces observed in fuel cells, microturbines, and storage

technologies. Aspect of the control design is that communication among microsources is unnecessary for basic microgrid operation. Each microsource controller should respond effectively to system changes without requiring data from the loads or other sources. Operation of the Microgrid assumes that the power electronic controls of current microsources are modified to provide a set of key functions.

The CERTS executive summary report in [34] presents the results of ongoing investigations on development of high power electronic systems for distributed generation systems using standardized approaches for integrating the components that comprise power converters. Distributed technologies are specified to represent a substantial portion of future increment in conventional power generation capacity. Modern distributed generation technologies such as microturbines, fuel cells, wind turbines and photovoltaic systems essentially deploy power electronic converters such as rectifiers and inverters in order to supply utility standard ac power. The cost of power electronic systems represents a major portion of installation costs due to the complexity of the engineering and realization of power electronics system packaging. The custom designed power electronic inverter families result in sub-optimal economic performance in terms of engineering design, packaging, manufacturing, etc. Good opportunity exists for wide spread deployment of electrical power converters with low cost, reliability, robustness, proper functionality, and interchange ability. Motivation for a sophisticated standard approach to power converter design is found in the areas of digital electronics and computer architectures in around 2004.

As per [35] (in 2005), the CERTS microgrid consists of multiple devices that are viewed by the traditional power system. It should have dynamically acceptable characteristics for proper DER adoption. The necessary control for CERTS microgrid can be conceptually divided into three layers: (i) Microsource Controller, (ii) Protection Coordinator and (iii) Energy Manager.

(i) Microsource Controller: The task of the microsource controller is to maintain the health, stability and usefulness of local electrical infrastructure.
(ii) Protection Coordinator: The protection coordinator rapidly isolates feeder when fault occurs. Also it islands the microgrid from the utility during a fault on grid side.
(iii) Energy Manager: The function of energy manager is to optimize the use of individual DER devices. The main objective of energy manager is to minimize the total energy bill within the constraints of the system such as supplying heat and electrical loads, fuel costs and equipment performance specifications, limitations due to safety, fuel supply limitation and restrictions on noise or pollutant emissions. There should be one energy manager for entire microgrid. Energy manager should select the condition of minimum cost of microgrid. To perform all these functions properly, cost of the energy manager system will also increase.

The work in [36] presents Multiagent System (MAS) for control of a microgrid. In this work, mainly internal operation of a microgrid including its participation in energy market is discussed. In this work, the microgrid installed in the power system laboratory of the National Technical University of Athens is shown. The microgrid comprises of a PV generator as the primary source of power. The microsources are connected to the single phase AC bus via DC–AC pulse width modulated inverters. A battery bank is connected in the system. This microgrid is a test field for MAS application. The following agents are involved in the MAS application. An MGCC (Microgrid Central Controller) Agent announces the beginning and the end of a negotiation period for the market operation. PV is a Production Unit Agent that is dedicated to represent the photovoltaic panel. One battery unit is a Production Unit Agent to represent the battery panel. This agent can sell or buy energy from the market based on the state of charge of the batteries. The power system is considered as a Grid Agent that representing the grid which is assumed as a production unit or consumption unit with infinite capabilities. Load Unit Agent is representing the loads of the system. Power seller agents are the market player agents that bid directly in the market and represent the agents that sell power to the system. According to the assignment problem, these agents are the "persons". Power buyer agent which is market player agent that participates in the market and represent the agents that buy power from the system. According to the assignment problem, these agents correspond to "objects". However, the concept presented in this work uses MAS technology for controlling a microgrid. Classical distributed algorithm based on the symmetrical assignment problem for the optimal energy exchange between the production unit of microgrid and the local loads including the main grid is applied.

Around the year of 2006, it is observed that integration of DER technologies started to be well accepted. The objective of the work in [37] is brief synthesis of the situation and the regularity environment concerning the development in France in particular and Europe in general. The technical issues for DER integration are briefly reviewed in this work which shows that different issues are at stake with the advent of DG on distribution network. The issues are steady state and short circuit current constraints, power quality, voltage profile, active and reactive power including voltage control contribution to ancillary services, stability and capability of DG to withstand disturbances, protection aspects, islanding and islanded operation and system safety. Depending upon a country's law, power sector economy, voltage and frequency levels etc, and these issues may vary.

The research activities in Europe on integration of DERs are reviewed in [38]. As per this report, Security of Energy supply, Climate Change and Sustainable Economic Growth, these three elements provide the main drive for energy research. The Security of Energy supply is explained on the basis of lack of adequate reserves of fossil fuel, such as oil, which is increasing the risk to the security of energy supply in several countries. It can be protected by further development of indigenous and renewable energy resources. Beside the issue of security of supply, major disadvantage of fossil fuel is the emission of Carbon di-oxide gas when fossil fuel is burnt for generation of electrical power. As per Kyoto Protocol, environment friendly and cost effective technologies needed to be deployed in the research of DERs worldwide. In this aspect, integration of DERs can play a major role for supply of environment friendly green power. Generation of electrical energy using clean energy technology will help to our economy by contributing to technological innovations, increasing European competitiveness, unlocking the huge potential of global markets. FP 5 and 6 projects financed sorting into the following strategic research priorities as presented in [22]. The issues are—(i) New approach for large scale implementation of DERs in Europe, (ii) Energy storage technologies and systems for grid connected applications and (iii) development of key enabling technologies.

From the year 2006, as reported in [39], DERs are becoming popular day by day and present centrally located generation, transmission and distribution are expected to evolve into an infrastructure where microgrids are common to exist. The successful operation of integrated DERs defined as microgrid depends on the different methods and techniques deployed in integration. These techniques should be economic, robust and environment friendly to generate electrical power. In [39], it is realised that a common standard benchmark model for microgrid testing is highly needed for successful operation of the microgrid

system. Strunz [39] reports that, CIGRE HVDC benchmark model is aimed at creating a common reference for HVDC control studies since topology of HVDC system is well defined. But for studies of DER based models, it is not possible to define single benchmark model for all types of microgrid. The problem of finding standard bench mark model is dealt with CIGRE Task Force (TF) C6.04.02 to establish a common basis in the form of benchmark system for integration of DERs [39]. With the continuous advancement of DER integrating technology proper system planning is essential based on location of resources and their interconnections [10]. As reported in this reference, the US department of energy (DoE) has developed and planned a roadmap for widespread deployment of DERs by the year 2020. The work presented in [10], addresses the sitting aspects of optimal microgrid architecture which considers the factors like deployment cost and savings gained by the application of CHP (combined heat and power) technology. This analysis is performed by applying non linear programming and simulated annealing optimization using a 6-bus test system.

In the year 2008, the larger role of microgrids paradigm based on expansion and reinforcement of the centralized grid is justified [40]. In this reference [40], microgrid is presented as an attractive means for accommodating wide range of growth needs and the highlighted features to be incorporated in control approaches of microgrid technology are autonomy, compatibility, stability, scalability, efficient and economy based on cost and market.

The idea presented in [41] addresses an approach to hierarchical integration of DC and AC microgrids containing distributed energy resources (DERs) into the existing power system. In this work, the authors attempt to define physical and architectures that permit effective management of microgrid system. The vision of microgrid proposed in [41] is applicable both in DC and AC zones. AC and DC zones will hierarchically integrate heterogeneous sets of DERs into the existing power distribution system. This approach is critical since the aggregation at any level must represent itself to the next higher level as a single self controlled entity. At the top level of hierarchy, the collection of all DER units and local DC and AC loads within the microgrid appears to the utility grid as a single self controlled largely efficient single unit.

The proposed approach presented in [42], is fundamentally same as mentioned in [41]. This approach uses a hierarchical framework with both DC and Ac links to implement microgrid as shown in the figure below. In this architecture a heterogeneous set of DERs are integrated into a three level hierarchy through advanced power electronic devices and appropriate control mechanism. In this work, three hierarchical modes are suggested.

(i) Integrating generation and storage units into combo sources via DC links.
(ii) Integrating combo sources into microgrid via AC links.
(iii) Interconnecting microgrids with utility grid via synchronous links.

Infotility's GridAgent ™ software is being used for large scale integration of distributed energy and renewable energy resources into distribution system. Purpose of using this software is to create an intelligent power network including management of microgrid control. As reported in [43], demonstration of GridAgent ™ software is implemented in the network of Con Edison of New York's distribution system.

The confidence and expectations on integration of distributed energy resources are gradually increasing day by day and the concept will provide huge operational benefits to power utilities, industrial and domestic loads by supplying "Clean Energy" to the human civilization. At present, smooth integration of distributed energy resources is not the only challenge for microgrid. In addition, the new developments and implementation of new technologies and applications in distribution management can help drive optimization of distribution grids and assets [44]. All these depend upon development of an advanced DMS (Distribution Management System).

Electric power system is undergoing remarkable change due to the need of environmental compliance and energy conservation. We need better grid reliability, improved operational efficiencies and customer service for satisfactory operation of smart grid [45]. This reference [45] reports on challenges with large penetration of intermittent resources. In this context, the challenges are based on the following challenging issues, such as transmission system issues, distribution system issues, interconnection standards, operational issues and forecasting and scheduling. Several questions raised on distribution circuit congestion, demand response while moving from a load following to load shaping strategy. Also critical role of information and automation technologies in smart grid issues were discussed.

Vaccaro et al. [46] describes an integrated framework with service oriented architecture by means of modeling, monitoring, control, communication and verification. The advanced framework based on the service oriented architectures for integrated microgrid modeling, monitoring and control are shown in the above figure proposed by [46]. It is reported in this reference that the rapid development of the information and communication technology has shown the ways for possible economic solution by permitting more widespread intra and inter utility information exchange, diffusion and open access to a wide range of real time information.

The authors of [47] analyzed the characteristic of microgrid from evolutional view and the concept of architecture oriented assurance technology is proposed from the technology evolution and policy evolution. The technology evolution contains function evolution, role changing autonomy and role coordination. Policy evolution components are evolution of market rules, price mechanism and management mode. Also coordinated control strategy frame based on role autonomous decentralized system and its architecture is proposed in that work.

During literature survey on the aspects of integration of DERs it is further revealed that the latest technological development in this field of research, in recent years, is aimed at the maximum utilization of various types of renewable energy sources (RESs) due to great advantage of abundance availability and less environment impact. In this current year (2012), [94] shows analysis of the issues related with new energy strategy for the years 2011–2020 and investigated the impact of the strategies on the use of renewable energy. This analytical study states that the future energy needs and utilizations of renewable energy sources requires harmonization of efforts towards increased use of RESs with nature of development of energy needs. The authors of this paper recognize this approach of study essential for sustainable development of microgrid technology to meet future energy demand. A model of microgrid system containing mixed renewable generation technologies is proposed recently in [95] for fluctuation of real world data of residential energy consumption and weather variables. Wang et al. [96] presents latest research observations on renewable energy integration technology which is closely related with smart building and home automation, demand response and demand side management. As per this reference [96], the future smart grid based demand side management is associated with the effect of electric vehicle operation on future power system, emission trading, energy storage including markets and future power system operations driven by smart grid technologies and devices. RESs are being identified in [97] as significant option in supply side management for microgrid where it is proposed that renewable energy based microgrid is

most environment friendly with significantly less system emission. The literature review presented in [98] shows that the future challenges of integration of fluctuating powers from renewable energy resources should be coordinated in association with smart grid operation to extract the maximum of renewable sources to mitigate the scarcity of fossil fuel in future.

3. Operation and control of microgrid

The steady state and transient operation of microgrid is possible among dispersed microsources in the environment of power electronic based interfacing and control strategies for fast control of frequency and voltage magnitude [48]. Grid interfacing power quality compensator for three phases, three wire microgrid applications is possible based on the quality of power of microgrid and the current exchanged between microgrid and utility grid. In power electronic based inverter system, both positive and negative sequence component of currents are controlled to compensate the disturbances due to unbalanced utility grid voltage [49]. An accurate power control strategy is proposed in [50] for a low voltage microgrid which states that a virtual inductance can be connected at the output of interfacing inverter which can prevent the coupling between active and reactive power by implementing a predominantly inductive impedance in a low voltage system with line impedances resistive in nature.

The operation of a radial distribution network in an islanded mode is important for an increasing number of integration of renewable energy sources with traditional grid [51]. A control method for regulating rate of power increase of a microsource based on dynamic characteristic which can prevent stalling of generators under large load including regulation of powers between the microsources and load demand are proposed for uniform dynamic response with load following capability [52]. The improvement in dynamic behavior is also observed in [53] which present a control method applied on doubly fed induction wind generator to implement both frequency and voltage regulation capabilities. [54] Proposes a new method of coordinated voltage support in distribution networks with distributed generation and microgrids where it is reported that the traditional reactive power control is insufficient, instead, microgenerator shedding should be employed for large number of micro generator penetration. Non inverter based distributed generation is also effective if an internal combustion engine driven wound field synchronous generator can be used more effectively as a DG in a microgrid system [55]. For inverter based system, a method is proposed in [56] for power flow control between utility grid and microgrid through back-to-back converters facilitating real and reactive power flow between microgrid and utility grid. Varaiya et al. [57] reports that a smart grid is necessary to manage and control the increasingly complex future grid with large share of renewable energy resources, higher capacity energy storage with accurate infrastructure of sensors, smart meters, demand response and communications. In this context, it is observed from literature survey that latest research efforts are aimed to build a relationship between limited availability of power from RESs and demand-side consumption to extract the maximum benefit of RESs for the habitat in remote areas. For an example, [99] proposes introduction of prepaid metering system with some control functions which can act on the consumer demand facilitating supply of power from several integrated RESs. The amount of energy supplied is proportional to the monthly availability of limited amount of power from RESs to uniformly distribute power restricting a single user with high purchasing power to draw most of the power alone.

A linear time invariant robust servo mechanism controller for autonomous operation of a distributed generation and local load is proposed in [58]. This controller assures robust stability, fast transient response and zero steady state errors. The improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop is studied [59] to stabilize the microgrid system for a series of operating condition. Another important aspect is suggested in [60] for optimal generation scheduling to optimize microgrid operation. The provision of frequency control reserves is proposed for multiple microgrids [61] in the perspective of deregulated market too.

The idea of operating an inverter which would be acting like a synchronous generator is developed and proposed in [62]. Using synchronverters, it can be controlled as per same theory of control of traditional synchronous generators. Balancing microgrid power using a control method which regulates the set value of microgrid rms voltage at the inverter ac side as a function of dc link voltage is proposed [63]. Xue-song et al. [64] proposes hybrid control methods for grid connected and islanded mode to meet the specific quality, capacity and reliability of microgrid. A knowledge based expert system (KBES) is proposed for scheduling of an energy storage system (ESS) which is installed in a wind-diesel isolated power system [65]. A hybrid ac/dc microgrid and its coordination control are proposed in [66] and it operates in a grid connected mode or islanded mode. Since worldwide research effort is in progress on standardization of microgrids, [67] proposes the hierarchical control of droop-controlled ac/dc microgrids which is a general approach towards standardization of microgrid and it is divided in three types which are (i) Primary Control: depend on droop method, (ii) Secondary Control: allows restoration of the deviations produced by the primary control and (iii) Tertiary Control: The power flow between microgrid and external grid is controlled by this method.

4. Microgrid power quality

Harmonic currents generated by non linear loads such as SMPS, variable speed motors, drives computers, power electronic inverters are applicable for microgrids. Most power systems accommodate harmonic current up to a certain level but when it becomes significant, it will cause communication errors, overheating, excessive line losses, spurious tripping of circuit breakers etc. [68]. Many research papers are developed for analysis of power quality based on harmonic problem in low voltage systems. Since microgrids are low voltage system, power quality is a serious issue for this kind of system and to be handled carefully [69]. Voltage dips are often responsible for disrupting the operation of sensitive electronic components which is very frequent in DG system such as microgrid [70]. Power electronics based inverters have inherent effect of harmonic injection in microgrid. Weiss et al. [71] proposes design of a voltage controller for dc–ac converter supplying power to a microgrid. Among different power quality parameters, the voltage total harmonic distortion is important and often analyzed in a specific way [72]. A power electronic interface system is presented in [73] which reports on solution of harmonic problem based on resonant passive filters. Microgrid power quality is an emerging area of research and a research on microgrid energy supply and filtering system based on inverter multiplexing is reported in [74]. Voltage and current THD (total harmonic distortion) with different DG unit and load configuration are studied in [75] with different microgrid configurations and simulation is performed applying negative sequence filtering in control system of converter to reduce voltage and current THD for unsymmetrical loads. Using universal active power line conditioner (UPLC) and a unified power quality conditioner (UPQC), the active filter in single phase high frequency microgrid is evaluated [76]. A fast and accurate method is proposed in [77] to estimate the fundamental frequency of an electric power system such as microgrid suggesting robust frequency estimation method for distorted and imbalanced

three phase system using discrete filters. A fuzzy based local controller is proposed in [78] exploiting the inertia of a wind turbine with DFIG proposes [79] a cost effective simple and effective method to prevent islanding of grid connected inverters. In addition, the present research trend on power quality of microgrid is also focussed on remedial measure of microgrid under unbalanced condition. A new control strategy is proposed in [100] which is applicable to islanded microgrid system under unbalanced state due to addition of single phase load. The medium voltage microgrid shown in [100] comprises of few electronically interconnected DG units. The proposed control strategy suggests for using a proportional resonance controller, a droop control scheme and a negative sequences impedance controller which reduces the negative sequences current under unbalanced state to improve the power quality of microgrid.

5. Microgrid protection

Microgrid protection issues must be dealt with the situation when utility grid experiences abnormal conditions and there are two specific types of problem to solve. First one is the behavior of microgrid when a fault occurs at the grid side and secondly, providing sufficient protection coordination when it operates in islanded mode [80]. The protection coordinator would rapidly isolate feeder fault and islands the microgrid during a fault from one another. Also necessary protective relays are needed to be placed strategically throughout the grid including control circuit to trip these relays in time [81]. CERTS suggested necessary steps and aspects on operation of microgrid in abnormal condition due to occurrence of fault [80,81].

Protection of microgrid during utility voltage sags, large line currents in distribution feeders are proposed in [14] through RL feed-forward and flux charge model feedback algorithm for controlling a series inverter connected between the microgrid and utility grid. Kroposki et al. [82] suggests development of a high speed static switch for distributed energy and microgrid applications. This static switch is a fast acting power electronic based semi-conductor switch [82,12] along with digital relays [13]. Distance relay response is analyzed in [83] for converter dominated microgrid and a method is proposed to limit a fault current in a faulty phase by reducing the converter output voltage. Protection of microgrid with a high penetration of inverter coupled energy sources is proposed with a protecting strategy to avoid inverter disconnection during faults including detection of type of fault in [84]. In [85], the main challenge of the protection due to current limiting state of the converter is overcome by admittance relays. [86] proposes a low voltage dc microgrid protection system where dc microgrid is used to interconnect DERs and sensitive electronic loads. As reported in [101], the stability of microgrid system depends on the nature of load and control techniques employed on the DGs. Microgrid stability in forced islanded condition due to occurrence of fault is studied in [101] in which combination of R-L-C and induction motor are used as loads. It proposes that microgrid operation may be unstable in presence of induction motor while the fault is being isolated within a typical clearing time. So the nature of load is very important for stable operation of microgrid and detailed study of faulty situation in presence of all possible types of load is essential for satisfactory operation of microgrid.

6. Microgrid stability

The dispersed type distributed generators are expected to be deployed in a stable condition in the operation, control, and protection. Voltage and frequency stability within the defined limits of microgrid operation needs investigation [87]. The effect of protective limiters and characteristics such as the genuine inertia of the generation set must be taken into consideration in stability studies in order to accurately represent the overall dynamic characteristics of local distributed generators. The work in [87] studies three fundamental aspects; such as (i) the development of a reciprocating engine/ generator set model; (ii) the laboratory testing of an experimental test rig; and (iii) the influence of a volts-per-hertz ratio (volts-per-hertz ratio) limiter on the generator dynamic response. In [88], detailed analysis is done on a microgrid system with a constant power load and it is observed that constant power loads make the system to be unstable due to their negative impedance characteristics and this is proved for the microgrid system by observing the location of the system poles. As per [89], application of a distribution static compensator (DSTATCOM) in an autonomous microgrid with several distributed generators (DGs) can enhance system stability. The credibility theory is analyzed to investigate the uncertainties on small signal stability problem of microgrid [90] and uncertainties such as random fluctuation generations and loads in a microgrid is to be effectively analyzed for small signal stability of the microgrid. The small-signal or steady-state stability analysis of an autonomous microgrid is studied in [91] and this topic is popular due to increasing penetration of distributed generation into power system. The small-signal modeling is studied using time domain simulation. Droop characteristics for grids with dominant reactance and resistance lines, the effect of reverse droop characteristics on small-signal stability and connecting lines with different X/R ratio are studied [91] for the stability of an autonomous microgrid. In [92], an adaptive feedforward compensation method is presented which can alter the dynamic coupling between a distributed resource unit and the host microgrid, so that the robustness of the system stability to droop coefficients and network dynamic uncertainties is enhanced. The proposed feedforward strategy does not compromise the steady-state power sharing regime of the microgrid or the voltage/ frequency regulation. The use of a coordinated control of reactive sources for the improvement of the dynamic voltage stability in a microgrid is proposed in [93] where the associated controller is termed as a microgrid voltage stabilizer (MGVS). As seen in [101], stability in microgrid system is highly related with the types of load connected with the system. Such as, constant torque loading may cause the microgrid to be unstable. It is also investigated in [101] that the shedding of few induction motors may be a possible solution to keep the system stable at the time of voltage dipping due to abnormal condition in microgrid.

7. Conclusions

From the literature survey on integration of DERs presented in this paper it is realized that feasibility of microgrid operation has many factors which are to be dealt with collectively. For successful integration of DERs, due care to be taken for proper operation and control, protection and stability issues. It is Interesting to note that all these issues are to be simultaneously and satisfactorily implemented during feasible operation of microgrid. The authors emphasized on technological evolution of microgrid beginning from the year 2000 onwards in this review work. But apart from challenges on technical aspects of microgrid the commercial issues are to be solved which may be different as per social, political and economical policies of a particular country.

In this review work, it is realized that it is necessary to investigate the feasibility of microgrid operation in the industrial fields and steady and dynamic state studies have been done in a plant equipped with many induction machines. The research teams of CERTS have

greatly contributed in the research arena focussed on the customer adoption of microgrid through proposing customer adoption modeling (DER-CAM). The application of energy management system (EMS) is found as an important feature of microgrid operation and control for maximum utilization of generator and supply of heat to the consumers. In addition, this literature survey shows scopes of power electronic based sophisticate application, specifically, static inverters with storage facilities provided with "plug-and play" functionality to provide required flexibility. The operation and control of CERTS microgrid in the form of integrated DERs in grid connected and islanded modes are found very useful with three layer control using microsource controller, protection coordinator and energy manager. In the research activities in Europe on integration of DERs, the three factors namely security of energy supply, climate change and sustainable economic growth found significant found significant. The environment friendly and cost effective technologies are needed to be developed in the worldwide research on DERs. In this paper it is also highlighted that the protection of microgrid system with fast solution of power quality issues along with stability of integrated dispersed DERs systems are essential factors to increase the acceptability of microgrid as an emerging power system.

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